MKID multicolor array status and results from DemoCam

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ABSTRACT

We present the results of the latest multicolor Microwave Kinetic Inductance Detector (MKID) focal plane arrays in the submillimeter. The new detectors on the arrays are superconducting resonators which combine a coplanar waveguide section with an interdigitated capacitor, or IDC. To avoid out-of-band pickup by the capacitor, a stepped-impedance filter is used to prevent radiation from reaching the absorptive aluminum section of the resonator. These arrays are tested in the preliminary demonstration instrument, DemoCam, a precursor to the Multicolor Submillimeter Inductance Camera, MUSIC. We present laboratory results of the responsivity to light both in the laboratory and at the Caltech Submillimeter Observatory. We assess the performance of the detectors in filtering out-of-band radiation, and find the level of excess load and its effect on detector performance. We also look at the array design characteristics, and the implications for the optimization of sensitivities expected by MUSIC.

Keywords: submillimeter arrays; superconducting detectors

1. INTRODUCTION

MKIDs are superconducting resonators operating at GHz frequencies, which have been developed into detectors for sub/millimeter applications, as well as applications at shorter wavelengths.[1] Under load from a power source at high enough frequency, a superconductor will have Cooper pairs broken, creating quasiparticles. This will cause a resonator will shift in frequency, due to a change in kinetic inductance, and simultaneously decrease the quality factor, Q, due to an increase in resistance. The resonant frequency and loss tangent are both proportional to the density of the quasiparticles. A probe signal coupling to a resonator under load would measure the frequency shift as a change in phase, and the Q change as a change in the signal's amplitude. Both of these changes can be measured through mixing the signal with a copy of itself.[2] In analog readout techniques, this is done using an IQ mixer, in which the outputs can be combined to find the complex transmission.

Using this readout technique, MKIDs are particularly interesting for sub/millimeter astronomical cameras because, by tuning the resonance frequencies of the individual detectors, one can couple hundreds of MKIDs to a single feedline. Probe signals at the resonance frequency of each MKID can be combined and sent in on the feedline, then read out separately. Hundreds of probes can be generated digitally, then converted into voltage and mixed up to the appropriate band.[3] The primary limit to the number of detectors can be read out is the bandwidth over which signals can be generated and recombined. This is because each resonator takes up a

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finite bandwidth determined by its Q; lower Q MKIDs will give significant response farther from the resonance frequency.

Several challenges are presented in the design of large arrays of MKIDs. The arrays must be designed to maximize mapping speed, including the largest number of detectors at the highest sensitivity possible. This requires significant optimization: low Q implies high frequency responsivity, but also leads to a higher probability of resonator "collisions", or unacceptable crosstalk.[4] More highly responsive resonators have lower Q under a given submillimeter load because the change in $1/Q$ and change in the resonance frequency are both proportional to quasiparticle density. Under the same load a more responsive detector, with larger frequency shift per quasiparticle, would have lower Q. The second challenge involves understanding and eliminating the effects of anomalous behavior in the arrays. These include, in particular, any problems with responsivity, with antenna beam patterns (which determine optimal coupling to astronomical point sources), and pickup not attributed to the antenna.

Here we look at the perfomance of MKID arrays of antenna-coupled detectors, sensitive to several colors. In the case of MUSIC, the plan is to have each antenna coupled to four independent resonators, each through a different bandpass, corresponding to roughly 150, 230, 290 and 350 GHz. A total of 144 resonators will be read out in each frequency grouping, comprising 500 MHz of bandwidth. To test this initial design, we use a total of 72 resonators in a 360 MHz band in the demonstration instrument, DemoCam. Instead of 150 GHz detectors, one resonator for each antenna was left completely uncoupled to the antenna to test the effects of dark pickup. DemoCam is designed to use the same warm optical configuration as Bolocam,[5] while having cold optics consisting of a single lens, giving a similar platescale of 7 ″/mm. This camera was used to test the basic operation and effectiveness of MKIDs at the Caltech Submillimeter Observatory (CSO), as seen in Figure 1. DemoCam had also been significantly redesigned to incorporate a two-layer Cryoperm® magnetic shield. The major optical elements, including the array, cold lens, and Lyot stop, are mounted to a central copper ring where the shield attaches and surrounds these elements. Figure 1b shows the interior design of DemoCam without the magnetic shield in place.

2. RESONATOR DESIGN

Original submillimeter MKID designs typically consisted of a niobium groundplane deposited on a substrate, typically silicon, through which is etched a coplanar waveguide (CPW) feedline. A CPW is a two-dimensional analogue of a coaxial cable, comprised of a center conducting strip separated by a gap from the surrounding ground plane. Original MKID designs consisted of simple CPW quarter-wave resonators, with one end open and one shorted to ground to create the resonance condition. The open end of the resonator was brought near the CPW feedline, coupling to it capacitively. The grounded end has a 1 mm-long section made of deposited aluminum, rather than niobium, as this is sensitive to light down to ∼90 GHz. A microstrip feedline from the antenna overlaps the aluminum section, allowing radiation coupled through the antenna to reach the absorptive part of the resonator.[6]

The simple CPW resonator design was found to have high frequency jitter due to dielectric fluctuations caused by two-level systems,[7] and was replaced by a resonator design with a larger interdigitated capaticor (IDC).[8] These have reduced frequency noise, and have made the frequency response direction competitive for reaching our sensitivity goals. However, these were found in initial tests to have high levels of both inter-resonator coupling and out-of-band pickup. The coupling comes about in cases of geometrically large capacitors nearby both spatially and in resonance frequency. While other techniques are being developed to solve this issue,[9] it has been found that physically separating resonators with similar resonance frequencies reduces the coupling to low levels acceptable for this application.

The second issue involves direct pickup. In the IDC geometry, millimeter waves can couple to the capacitor, and then break Cooper pairs in the aluminum absorptive section of the resonator. In effect, the capacitor can behave as an antenna. Due to its size, 1 mm × 0.5 mm, the beam would be significantly wider than the larger antennas, 4.2 mm × 4.2 mm, and more likely to contribute to excess load in addition to spurious response. Thus, it is important to design some way of preventing coupling either to warm surfaces or to sources of interest.

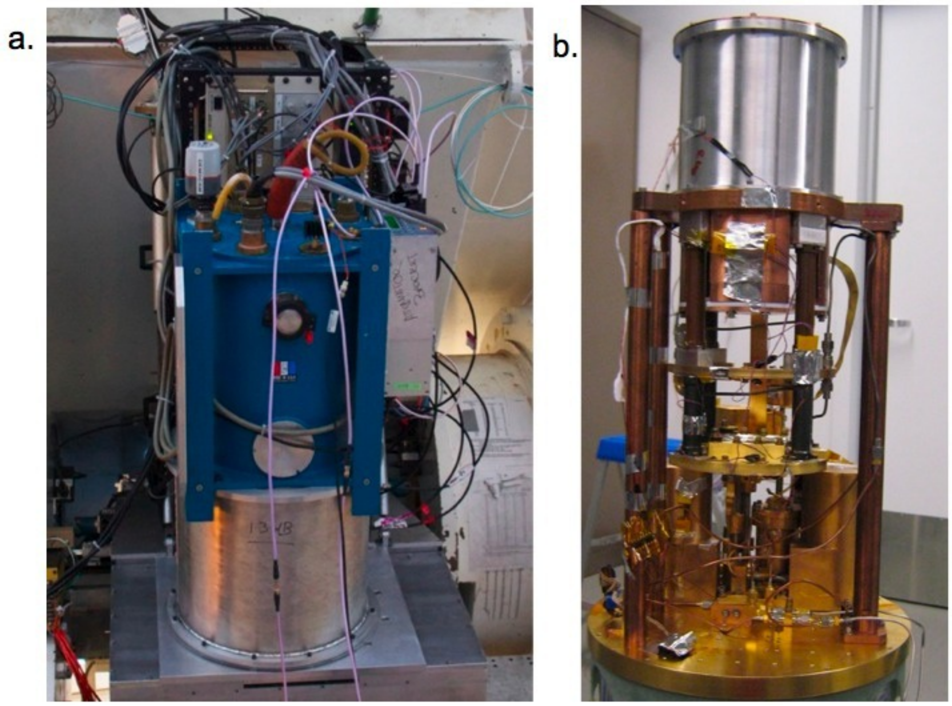

Figure 1. a) DemoCam mounted onto the Bolocam optics box at the Cassegrain focus at the CSO. b) The internal structure of the DemoCam, usually enclosed inside a two-layer magnetic shield.

The primary way this is prevented is through use of a stepped-impedance filter in line between the absorptive aluminum section and the capacitor. Figure 2 shows the new design. The resonators have a long niobium CPW inductive section leading from the capacitor to the aluminum. In that stretch, the width of the niobium center is made to vary between 1 micron and 16 microns, the larger width leaving only 1 micron gap width on either side. The lengths of the stretches vary to filter out different wavelengths in the millimeter-wave regime. This has the effect of reflecting those wavelengths due to an impedance mismatch, keeping the light from coupling to the aluminum. However, this is a very poor filter in the microwave, as the lengths of any of the strips are too short to affect them. This works out ideally, as microwave current from the feedline can still reach the absorptive section, but millimeter waves cannot.

The responsivity for this type of resonator is controlled by the thickness of the aluminum deposited. This aluminum will have a greater quasiparticle density under the same load, simply because the Cooper pairs are broken in a smaller volume. In addition, the effect of the kinetic inductance increases in thinner aluminum, yielding a higher frequency shift per quasiparticle created.[10] The thickness must be optimized for the high responsivity and the few detectors lost to high crosstalk "collisions".

3. RESPONSIVITY

3.1 Responsivity testing technique

The responsivity is generally tested by measuring response to hot (300 K) and cold (77 K) beam-filling Eccosorb$^{\mathrm{TM}}$ loads in front of the Dewar window. Under these optical loads, the quasiparticle density changes, leading to a measurable change in Q and resonance frequency. Under each load, a sweep of the transmission of probe signal is found by sweeping through probe signal frequencies as a function of time. This gives the transmitted probe signal as a function of frequency, which can be used to fit the resonator profile for these parameters. Thus,

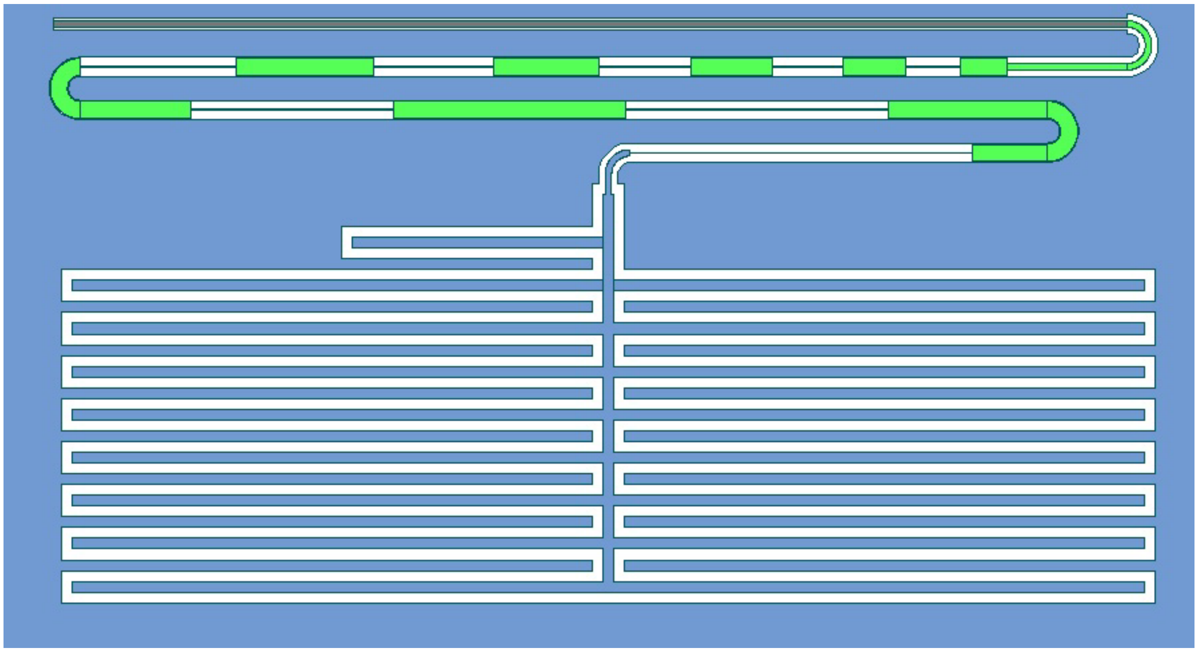

Figure 2. Diagram showing the resonator design, complete with stepped impedance filter. Here blue is the niobium groundplane, and white is bare substrate. The large capacitive section is roughly 0.5 mm^2. The stepped impedance filter is shown in green to highlight its effect, though it is also niobium. This shows how the center CPW strip varies in width to change its effective impedance. Although it is difficult to see, the green center strip never comes into direct contact with the groundplane, as there is always at least a 1 micron gap. The aluminum absorptive section is in gray.

the resonance frequency is not measured by the shift in a single probe at the resonance, as is done during observations, but by fitting a modified Lorentzian profile the transmission from many frequencies. By measuring the hot/cold frequency response, it is simple to find the expected response to a source at any power under an arbitrary load. This response is given by

$$\frac{df}{dP} = \frac{\frac{\delta f}{\delta T}(\sqrt{T_1} + \sqrt{T_2})}{k_B(\Delta\nu)} \frac{1}{2\sqrt{T_{load}}} \tag{1}$$

where T_1 and T_2 are the hot/cold load temperatures, plus excess load, and $\frac{\delta f}{\delta T}$ is the hot/cold response in kHz/K.

An alternative method involves the use of skydips at the telescope, which involve measuring the frequency shift as a function of the telescope's angle away from zenith. This uses effectively the same principle as the hot/cold loads, but uses the sky as a calibrated load based on the bandpasses. The atmospheric loading can be found by the atmospheric opacity, measured at 225 GHz at the CSO.[11] The atmospheric opacity can be scaled to the average opacity over each band in the camera by a simple factor. We take the average sky temperature to be 260 K, and can find the effective opacity in each band by scaling the 225 GHz opacity to the average over the bandpass. This gives the total loading in Kelvin, which can be compared to the hot/cold measurements by scaling appropriately. It is difficult to directly compare the dark response, because its effective bandpass is unknown and the sky load is highly variable with wavelength.

These measurements are typically performed at readout power much lower than the optical power. This allows the resonators to retain their undistorted, Lorentzian shape, which is easier to fit for frequency and Q. However, this does not take into account the effect of high power readout on the frequency shifts. High power is generally used to improve the signal-to-noise ratio, but can lead to a decrease in the responsivity.[4,12] This must be corrected for when comparing responsivity measurements from telescope results with those from sweeps of hot/cold measurements or skydips.

3.2 Non-antenna responsivity

With antenna-coupled MKIDs, any response through mechanisms other than the antenna can cause excess load or systematic errors in astronomical measurements. There are three primary ways in which light can cause response in an MKID focal plane, in addition to response through the antenna. The first is by direct coupling into the aluminum section, from free space into the absorber. The second method is by coupling through the interdigitated capacitor, which acts as an antenna to couple light to the aluminum. Finally, it could be caused by the substrate heating in response to optical load, which mimics a light response by thermally creating quasiparticles. Although it is difficult to differentiate between the first two cases, the third case can be distinguished from those two. One method is to use the fact that the timescale of thermal response is much slower, as it involves the heating of the entire device. If the response to a chopped source decreases with chop frequency, it is very likely thermal. Another method involves looking at the relationship between the change in the resonator's loss tangent and the change in fractional frequency. According to Mattis-Bardeen theory,[13] which governs the AC behavior of superconductors, these responses should have a well-defined ratio for each resonant frequency that depends on the physical temperature of the superconductor.[10] Both are proportional to quasiparticle density, but the frequency and temperature determine the constants of proportionality. The ratio of frequency-to-dissipation response was found to be higher than expected, indicating an elevated temperature and likely substrate heating response to changing optical power.

In the case of substrate heating, several adjustments can be made to minimize its effects. The first modification involves the anti-reflection tile, which matches the silicon substrate to free space over the wavelengths observed. In its original configuration, this consisted of fused SiO_2. This was replaced by crystal quartz SiO_2, which is less absorptive at high frequencies. The second change involved the addition of gold pads to the device groundplane. This allowed for gold wire bonds, with high thermal conductivity, to help thermally sink the array to the cold stage. The final adjustment is to increase the filtering in the optical chain, and thus reduce the power at the array. This reduces the direct pickup due to all circumstances.

Figure 3 shows the effect of gold wire bond pads and quartz antireflection coating. A vertical line is used to mark the division between light (antenna-coupled) and dark resonators: dark resonators are higher frequency and light resonators at lower frequency. This plot shows dramatic improvement from the array modifications, but less relative improvement from a metal mesh low-pass filter added into the filter stack. Although it is uncertain, this may indicate out-of-band pickup in addition to the thermal response.

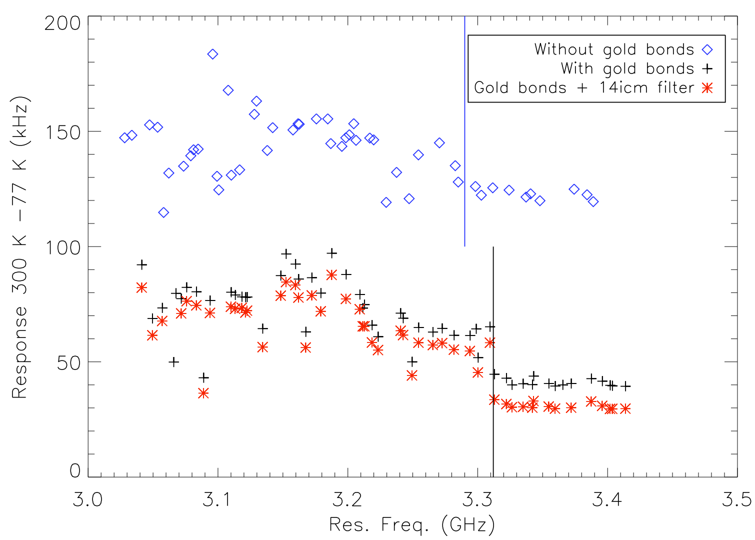

Figure 3. Total response to hot/cold loads for a device without heat-conducting gold wire bonds, and a device with them. Resonators to the right of the lines drawn are dark, i.e. not antenna coupled, detectors.

The dark response, even with the improved optics and gold wire bonds, is still on par with the optical response through the antenna. However, the response has a much wider beam pattern than the antenna. This makes coupling to the sky much smaller, as the effective beam will not couple well to the warm focusing elements at the telescope. Instead, much of this pickup will couple to warm, black surfaces around the focusing mirrors. Figure 4 shows the frequency shift from skydips – pointing the telescope to different elevations under the same atmospheric conditions. The dark response to skydips is much lower, relative to the light response, than in the case of beam-filling hot/cold measurements. Adding a polarizing grid reduces the relative response of the dark pixels. In Figure 4 they show the same response, but those with the polarizing grid were taken with higher atmospheric opacity ($\tau_{225GHz} = 0.13$ vs. 0.055 for the non-polarizer data), so one would expect a higher response. Therefore, coupling to the sky is greatly reduced. Coupling to point sources is even further reduced

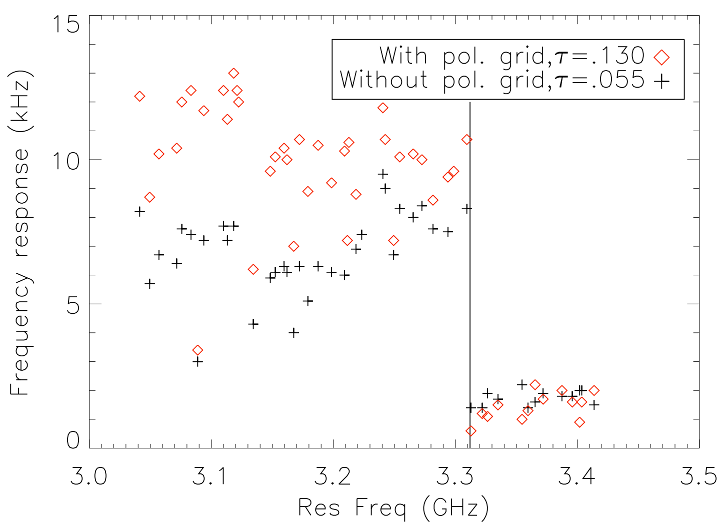

Figure 4. Frequency response to skydips for both dark and light resonators.

in these detectors. Figure 5 shows maps taken from resonators in the three bands as well as dark, all during the same observation. There is effectively no residual response in the dark antenna, despite the brightness of Mars (~500 Jy in band 3, nearly 5 orders of magnitude brighter than a typical submillimeter galaxy.) While the non-antenna response to astronomical sources is small, effectively all the responsivity from dark detectors in beam-filling measurements now contributes to an excess load. This direct pickup couples to room temperature black surfaces if it is not coupled to the sky. This extra loading will decrease responsivity and add a significant photon noise to the detectors. Therefore, it is in our interests to eliminate it completely, even if it does not pose a threat in terms of anomalous source response. To do this, we must understand where the pickup comes from. We have found that the array temperature response has been significantly reduced, but we do not know that it is entirely gone. The other methods of direct coupling are still possible, as well.

3.3 Optical efficiency and excess loading

It is difficult to make any absolute statements about optical efficiency given that we do not know the exact thickness of the aluminum absorber, and thus we do not know what the quasiparticle density is expected to be under load. However, if we make a reasonable assumption about thickness, we can convert the hot/cold measurements into efficiency. In the case of a similar device, in which the superconducting parameters had been measured under no optical load, the single-polarization efficiency was found to be 0.032 with an r.m.s. scatter in efficiency of 0.018. When taking into account the effects of the optical transmission, including through the Lyot stop, and reasonable assumptions about how uniformly the power is absorbed in the resonator, the median efficiency is still as much as a factor of 4 lower than expected. The exact cause is not yet known, but is possibly due to loss in the antenna microstrip dielectric.

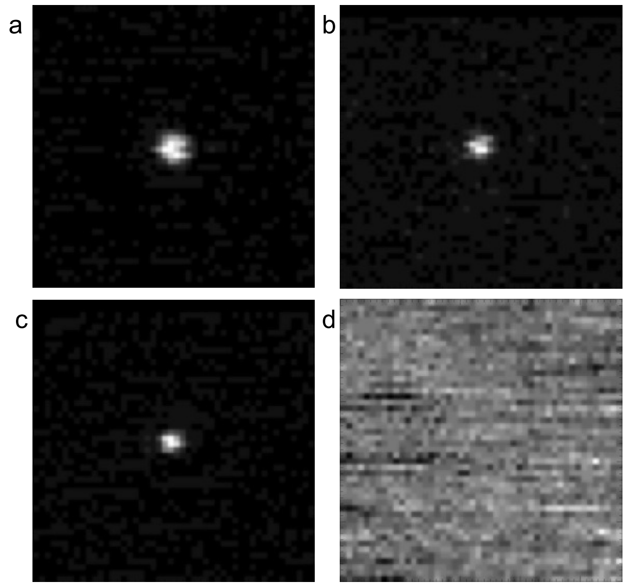

Figure 5. Frequency response in Mars observation from four resonators. a) Resonator antenna-coupled through a Band 1 (230 GHz) filter. b) Resonator antenna-coupled through a Band 2 (290 GHz) filter. c) Resonator antenna-coupled through a Band 3 (350 GHz) filter, d) Uncoupled or dark resonator. All the plots are peak-normalized, but have similar noise levels.

The other main contributor to reduced sensitivity is the excess loading. Due to the high dark response coupling to warm surfaces, a high excess load was calculated from skydips. The median excess was 120 K in Bands 1 and 2, and 190 K in Band 3. However, this likely understates the excess load for non-point sources, as it includes the small dark response in coupling to the sky. This large level both degrades the optical response and increases the photon noise in the detectors.

3.4 Optimal responsivity for arrays

The low optical efficiency may be partially offset by using thinner aluminum in the absorptive section of the resonator. Exactly how responsive these detectors can be must be considered in balance with how many resonators will be lost due to "collisions," or the case where two resonators are close enough together in frequency to have significantly overlapping response. This is complicated by the fact that thickness variations in the superconductor deposited can lead to varying resonance frequencies; the device measured here had a 5.3 MHz r.m.s. random scatter compared to the designed frequencies. In a 300 MHz bandwidth with 55 resonators, this is a significant scatter. For a resonator with a given Q, the fractional dropoff in response a distance δf away from resonance is given by

$$F_R(\delta f) = \left| \frac{1}{1 + 2iQ\frac{\delta f}{f}} \right|. \tag{2}$$

Thus, if resonances are too close together compared to their width (or Q), they will experience too high a level of crosstalk to be usable.

The DemoCam device discussed here was designed such that, with good optical efficiency and acceptable excess load, the typical Q for all three bands would be near 30,000 at the telescope. Under good sky loading conditions ($\tau_{225GHz} = 0.055$, ZA=60 degrees), the mean Q for this device, including the excess load from the optics box, was 37,000 $\pm$ 8,300. This led to only two resonators "colliding" over the 300 MHz usable bandwidth with nominal 5 MHz spacing between detectors. This collision is seen in Figure 6. The resonator Q will increase as the excess load due to direct pickup is reduced, but decrease as optical efficiency is increased. It is likely that

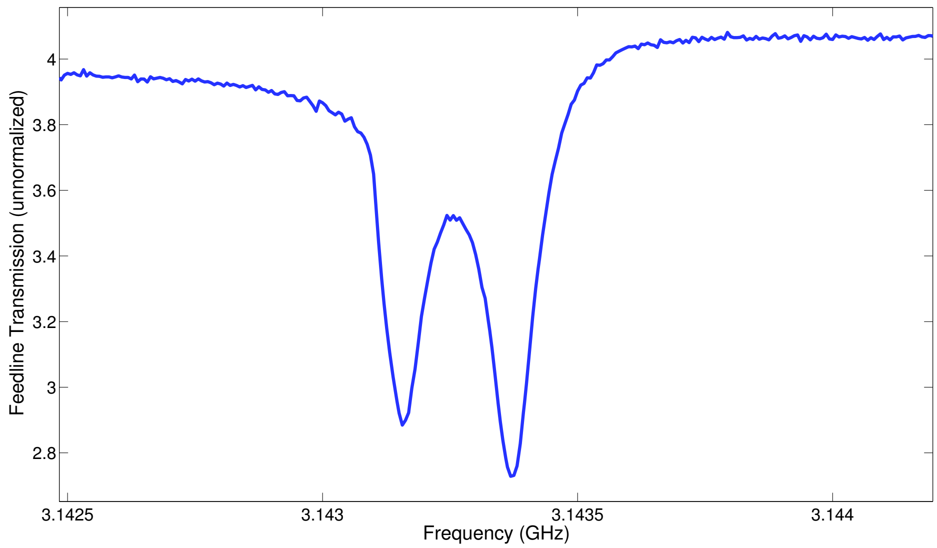

Figure 6. Two resonators "colliding" in frequency space. Here the measured crosstalk was found to be below the 10% level.

Table 1. Number of usable resonators in each band (maximum 36) given various frequency spacings (in MHz, columns 2-4) and 5.3 MHz r.m.s. scatter. Spacings correspond to usable bandwidth of 300, 400 and 500 MHz. Here we assume a cutoff threshold of 5 FWHM spacing for resonators to have acceptable crosstalk: if the spacing is less than 5 FWHM, they are deemed to have "collided" and are unusable.

Q	2.1 MHz	2.8 MHz	3.5 MHz
10,000	12	18	22
15,000	20	24	27
20,000	24	27	29
30,000	28	30	31
40,000	30	32	33

either thinning the aluminum layer or increasing the efficiency will not cause a major loss in number of usable detectors per band, but may significantly decrease frequency NEP. Typically, one would like the response from adjacent MKIDs to be at the level of a few percent. In an array of 36 resonators for each color, the calculated number of expected usable detectors per band is shown in Table 1. This shows that the Qs resulting from an increase in optical efficiency, or from thinner aluminum, may yield acceptable losses in detector number if the excess loading is reduced.

It must be stressed that the MKIDs discussed here are in the limit of internal Q being set by the quasiparticle density from optical loading. In this limit, improving the frequency shift for a given optical load will also degrade the Q under the same conditions. If the signal-to-noise ratio is limited by phase or gain fluctuations from amplifiers or electronics, the noise affects the phase shift of the probe signal. For a small signal, the phase shift for an optimally coupled resonator goes as $Q\Delta f$, where Δf is the frequency response to a source. An increase in frequency response per quasiparticle will not increase the phase signal, because the Q decreases proportionally to the increase in frequency shift. Increasing the frequency responsivity helps overcome internal resonator noise, such as two-level system noise, but not external (e.g. amplifier) noise. Thus the amplifier and electronics noise will set the fundamental limit on sensitivity, no matter how responsive the detectors are. If the MKIDs are amplifier noise limited, the best strategy is to design the array with the largest number of usable resonators in a given bandwidth.

4. RESPONSIVITY AND SENSITIVITY AT THE CALTECH SUBMILLIMETER OBSERVATORY

The responsivity of the detectors is recorded in timestreams in units of voltage change due to phase and amplitude shift, a complex number, z=I-iQ. Here I and Q represent the outputs of an IQ mixer, Q representing the phase shift and I the amplitude shift. This effectively gives the complex voltage transmitted through the cryostat at the resonance frequency. This voltage depends on the readout power used, as well as on the resonator Q, and the frequency of the probe signal relative to the resonance frequency. This can be converted into a frequency shift by taking a sweep of the transmitted signal around the resonance frequency – near the resonance frequency, this will give us a calibration of the change in frequency per volt change in complex transmission. In other words, the goal is to calibrate $|dz/df|$ in order to put the response in units measurable in the laboratory. With a fine enough sweep of probe signals varying in frequency, typically < 3 kHz, it is possible to calibrate the signals correctly.

Once the signal is converted into frequency (or the fractional frequency change, $\Delta f/f$, which is proportional to $\Delta\frac{1}{Q}$) and dissipation changes, it can be properly calibrated and compared to responsivities inferred from loading measurements. In this way, we can see if our coupling to point sources is as efficient as we expect. This must be accompanied by the caveat that it is not a proper direct comparison, because the response is decreased due to the high readout powers used.

Figure 7 shows the Gaussian-fitted peak heights for a resonator as a function of atmospheric opacity smoothed with time. The response to point sources inferred from skydips, including the effects of excess load and dark response, is also plotted for comparison. In red is the expected response reduced by a factor of 0.7, which is near what is found to be the reduction in frequency response at higher power. In addition are plotted the Gaussian-fitted peak heights to the source for this resonator. Poor fits to the point spread function for individual observations are included in the plot, but do not lie with the trendline. There still appears to be a discrepancy between the observed peak heights and those expected. But considering the uncertainties of responsivity reduction with power and the precise loading due to dark response, this is at a fairly low level.

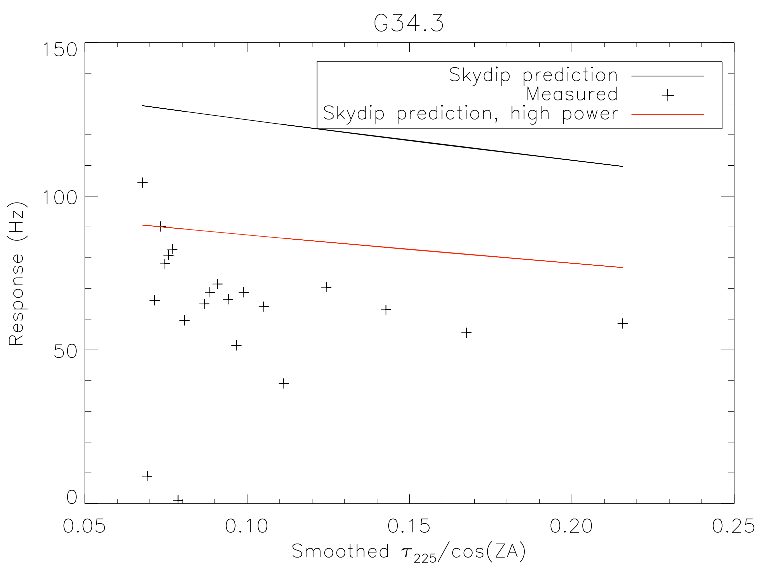

Figure 7. The response to the calibration source G34.3 for a typical band 1 resonator.

It is worth noting that the calibration is relatively flat with atmospheric opacity. This is primarily caused by the large excess load from the non-antenna pickup. With lower excess load values, the peak heights would be a much stronger function of atmospheric load, and more sensitive overall.

5. SUMMARY AND FURTHER CONSIDERATIONS

The responsivity picture seems to fit together: although point sources seem to couple to detectors with slightly lower efficiency than beam-filling blackbodies do, the response is near what we would expect. The sensitivity for laboratory measurements[12] and telescope measurements[14] has been found to be a factor of several over BLIP at the frequencies of interest. This picture reveals that there are still problems to solve for antenna-coupled MKID arrays to reach BLIP for sky loading exclusively. There are two primary goals to accomplish this - to reduce or eliminate dark pickup, and to improve antenna efficiency. There is reason for optimism in overcoming these crucial obstacles.

From a systematic perspective, the effective dark coupling to point sources at the telescope seems negligible. In addition, significant progress has been made in the reduction of dark pickup, both from temperature fluctuations and from direct coupling. Further developments will likely drastically reduce this in the future. To reduce thermal pickup, this includes a higher density of gold wire bonds to reduce temperature fluctuations, or improvements in the clamping of the array to the cold stage. To reduce coupling from the IDC, a re-design of the stepped impedance filter to work better at smaller frequencies combined will be combined with a metal mesh low-pass filter, thus improving the reflections of millimeter-waves away from the aluminum absorber. Finally, the geometry of the aluminum absorber can be altered to reduce direct pickup if that is found to be an issue. These will be tested systematically before the deployment of MUSIC.

This leaves the efficiency of the antennas in coupling to the resonators. While this may be solved by improvements in the dielectric in the antenna microstrip feedlines, the effect can also be partially offset by using thinner aluminum. Thinner aluminum leads to a higher frequency response for a given load, helping to overcome any resonator noise (i.e. two-level system noise). These effects must be carefully optimized to ensure that enough resonators are usable as detectors without colliding in frequency space. With these problems addressed, MKIDs should achieve near background-limited performance for a large number of detectors in the near future.

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